Continued Search for the Carbon Sink: Considering Interactions in an Integrated Assessment Framework

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Land use Land Cover Change as a Climate Change Driver

Why Feedback Scenarios are CRITICAL?

Logical / Process Flow….

- LULC Change (albedo, vegetation characteristics)
- Leads to Surface Energy Balance Change
- Leads to surface temperature changes
- Associated with evapotranspiration and surface hydrological changes
- Leads to terrestrial NPP / carbon assimilation rates
- Leads to vegetation characteristics / LULC changes
- Go to 1……

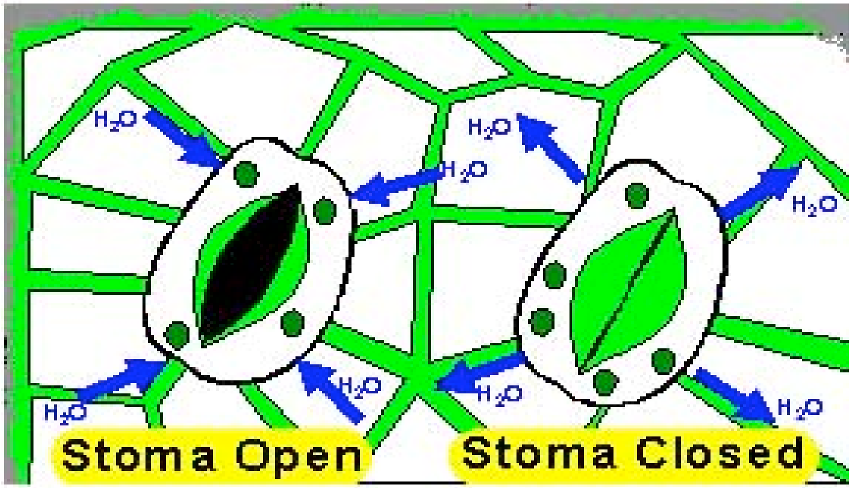
Land use Land Cover Change as a Climate Change Driver
Why Feedback Scenarios are CRITICAL?

Not considering the LULC feedbacks will lead to

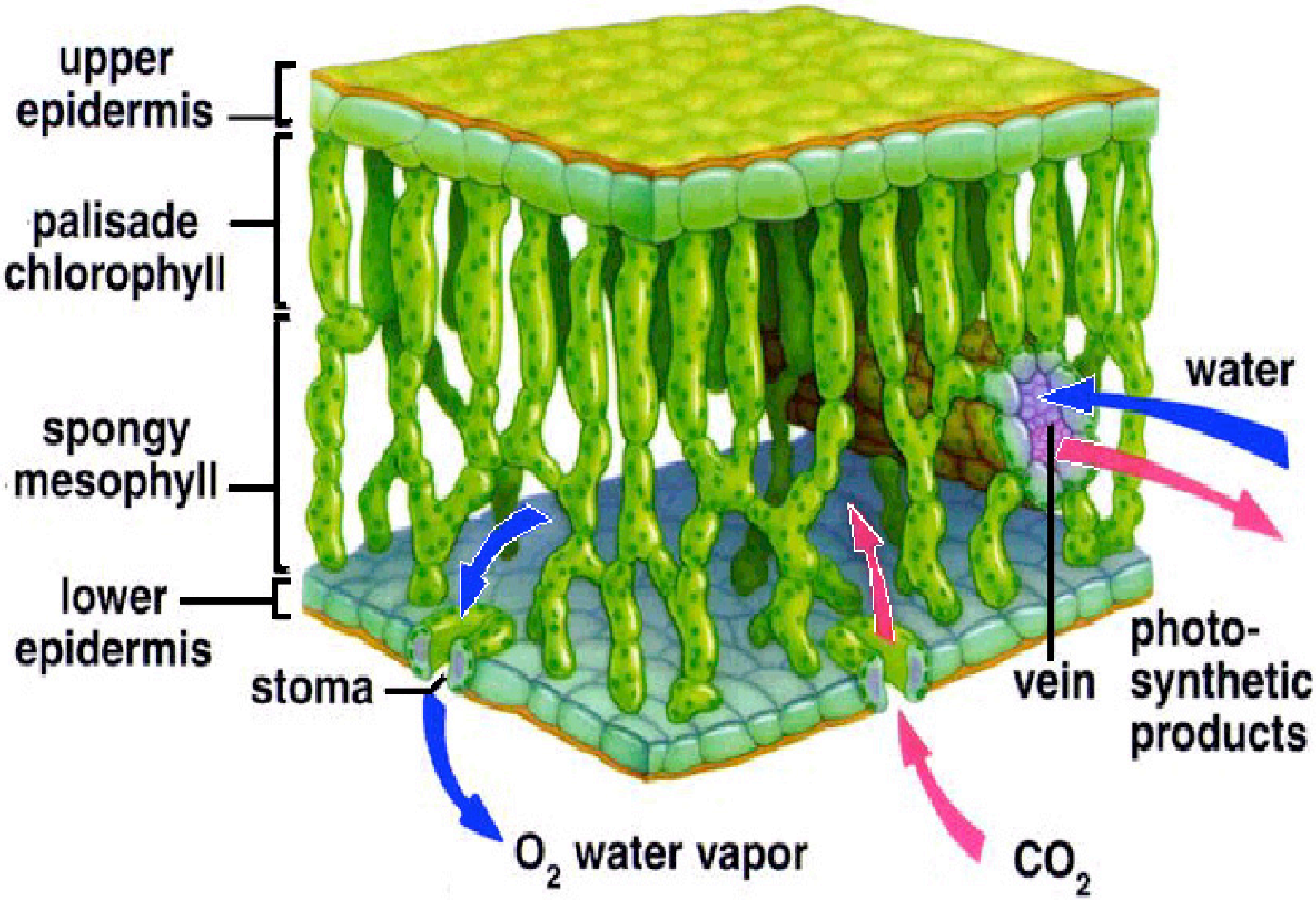
- Failure of Carbon Management Policy
- Failure of Climate Policy
- Unintentional drought / hydrological effects
- Jeopardizing of integrated assessments and international negotiations and scientific credibility

Stomate Interface Surface - Atmosphere Energy as well as Carbon Exchanges

LEAF C/S 750 x

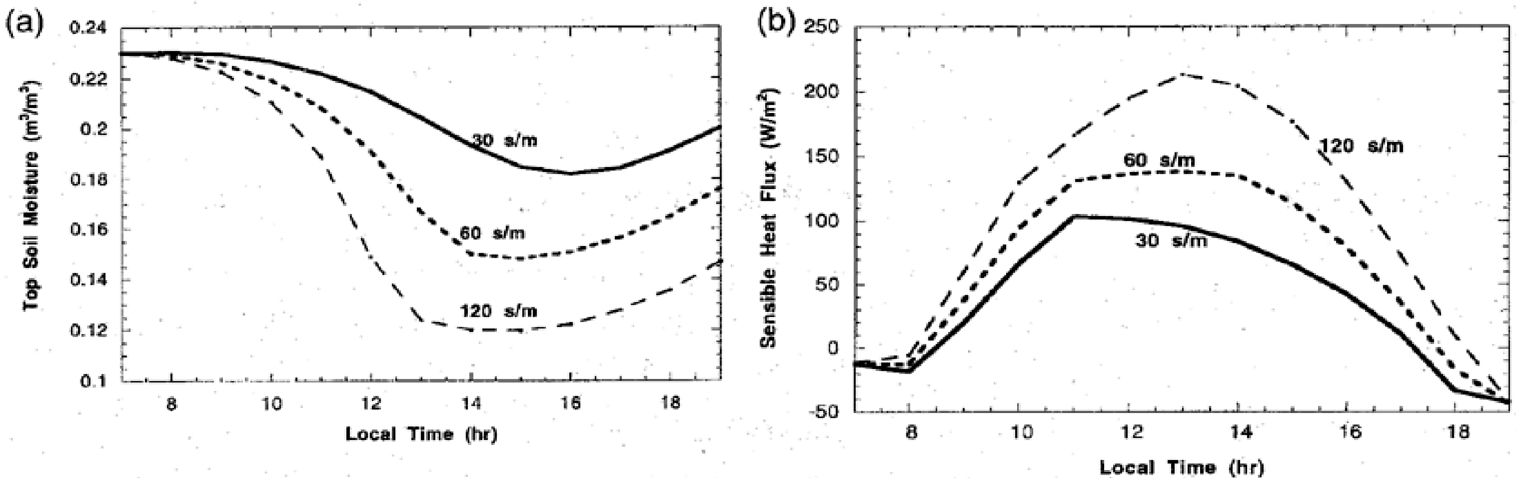


STOMATE AS VALVES


upper
epidermis
palisade
chlorophyll
spongy
mesophyll
lower
epidermis
stoma
water
vein
photo-
synthetic
products
O_2 water vapor
CO_2

Effect of Change in Stomatal Resistance (inverse of conductance, which is linked with carbon assimilation rates) on the simulated boundary layer structure

[Typically, Rs change by factor of 4 (from 30 to 120 s/m), altered energy fluxes by factor of 2!]



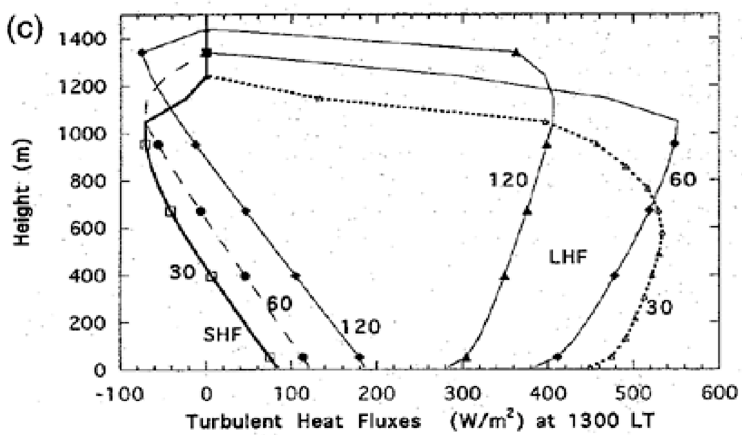
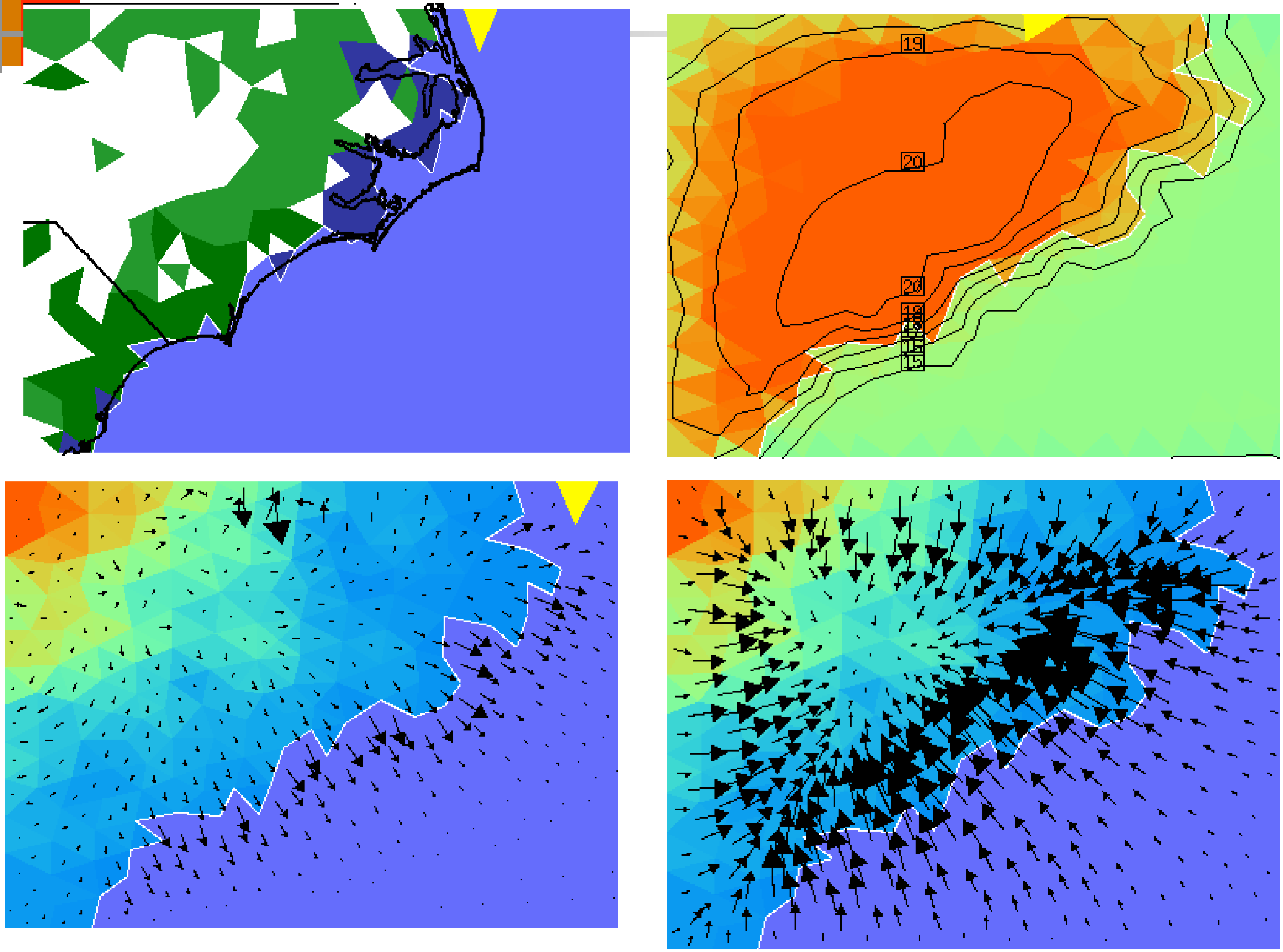


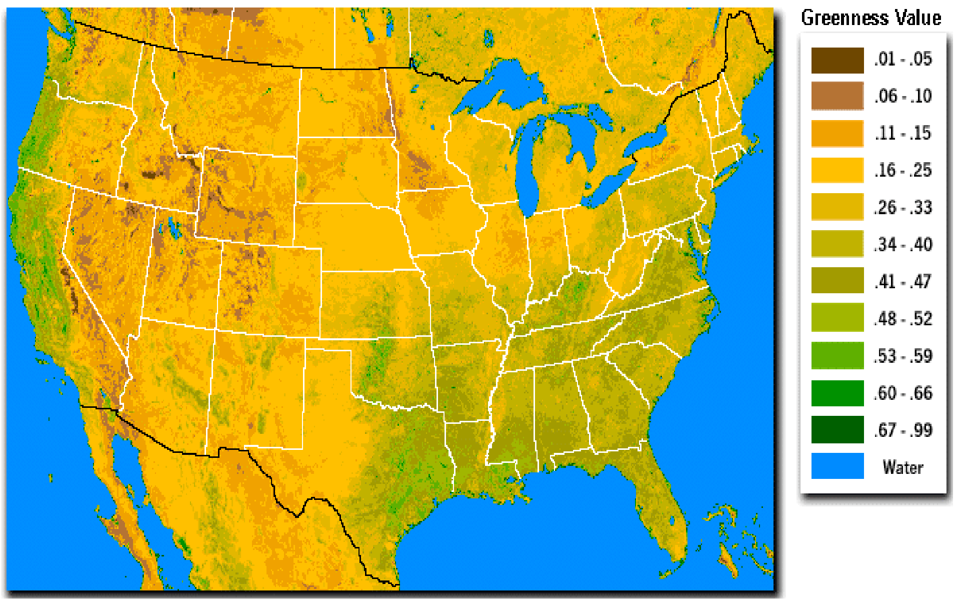
FIG. 1. (a) Resulting top soil moisture (10-cm-thick layer) variation for changes in the initial $R_{s\,min}$ values. In the figure, 30, 60, and 120 refer to the $R_{s\,min}$ values (s m^{-1}) considered. (b) Same as in (a) except for surface sensible heat flux. Notice the peak values for the extreme cases (30 and 120 s m^{-1}) differ by almost a factor of 2. (c) Same as in (a) except for turbulent heat flux profiles. Sensible heat fluxes are plotted on the left and are denoted by SHF, while the latent heat fluxes are on the right and are denoted by LHF.

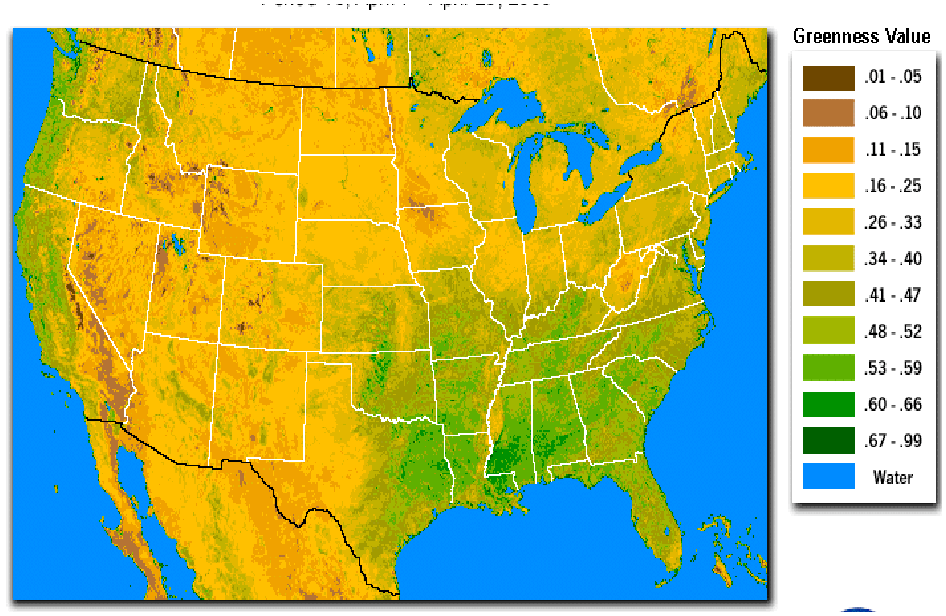
Mesoscale Circulation due to Surface heterogeneity



Differential Land Surface Cover is an inherent feature affecting earth system applications due to both natural variability and human intervation

- March April

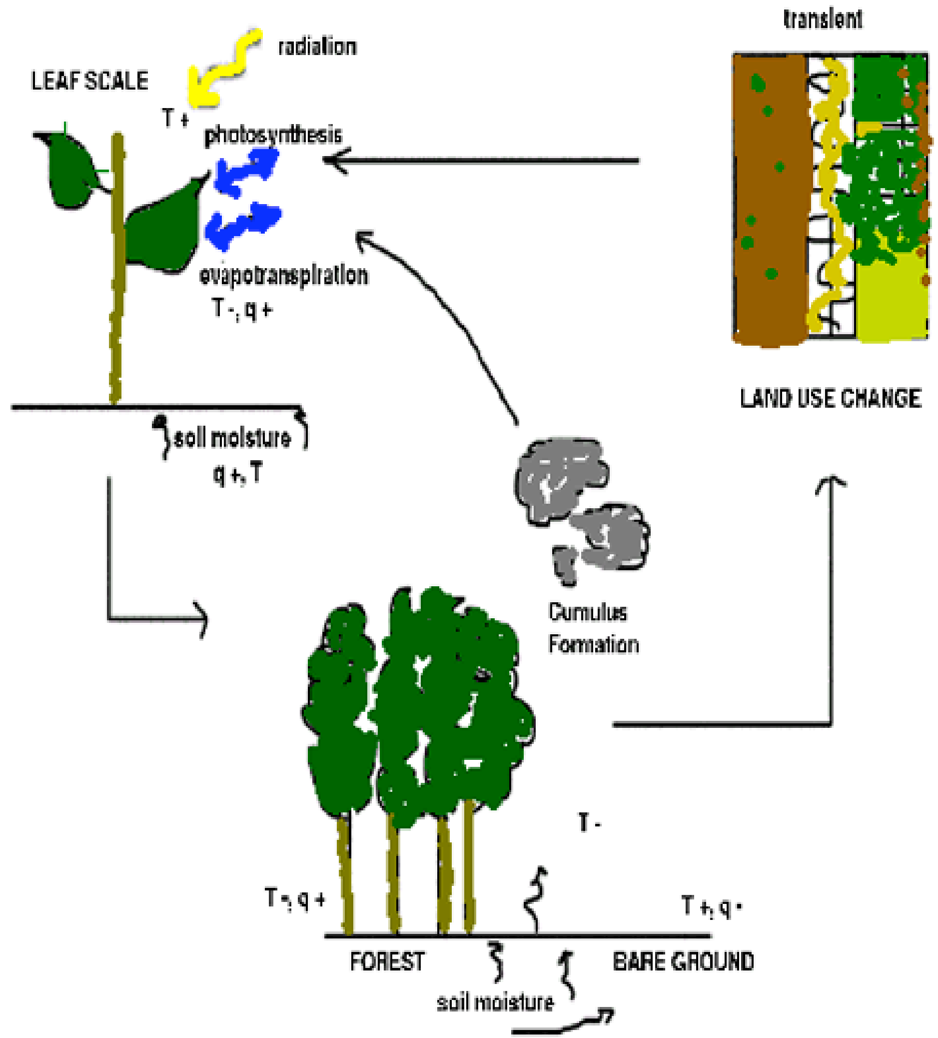


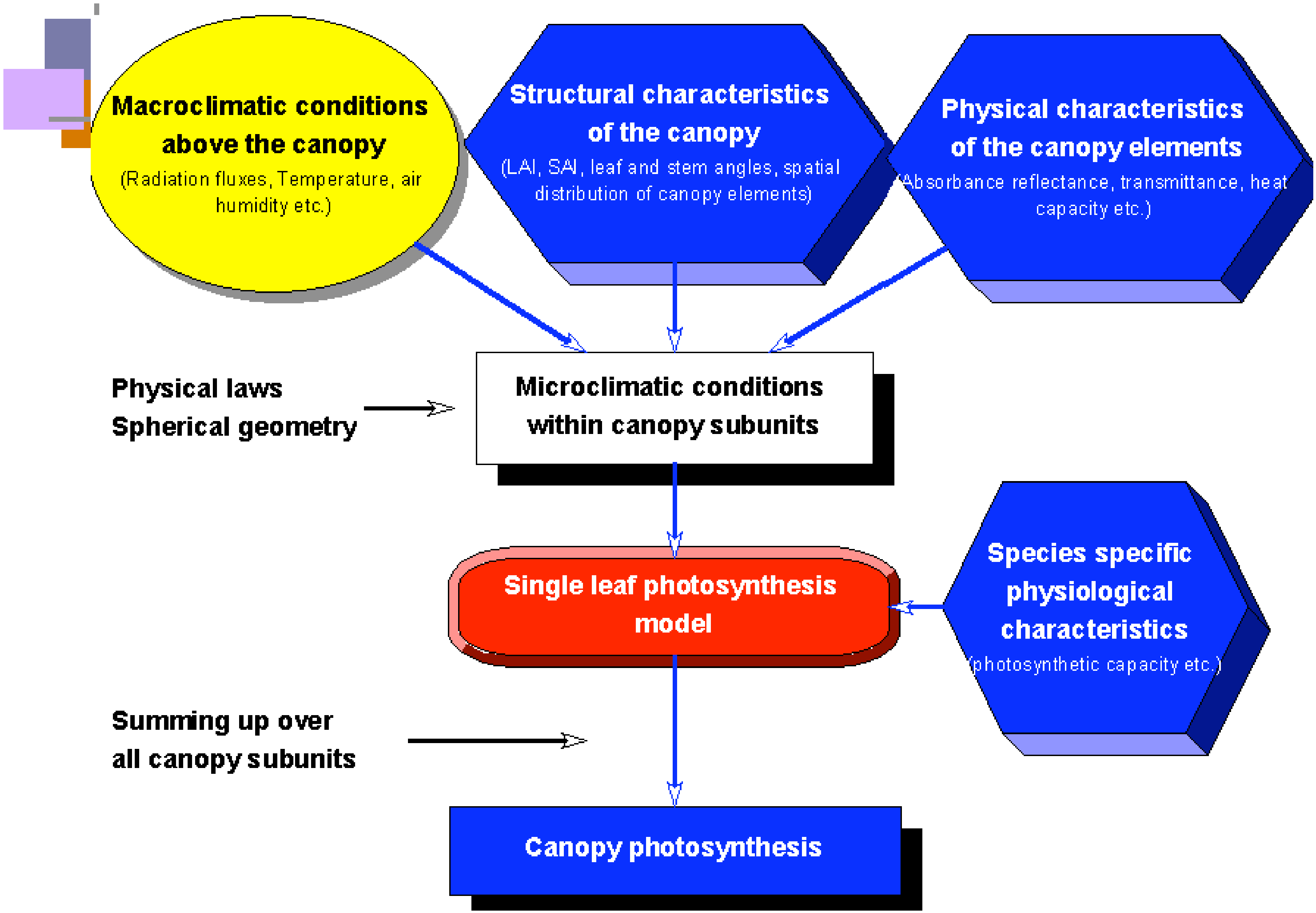


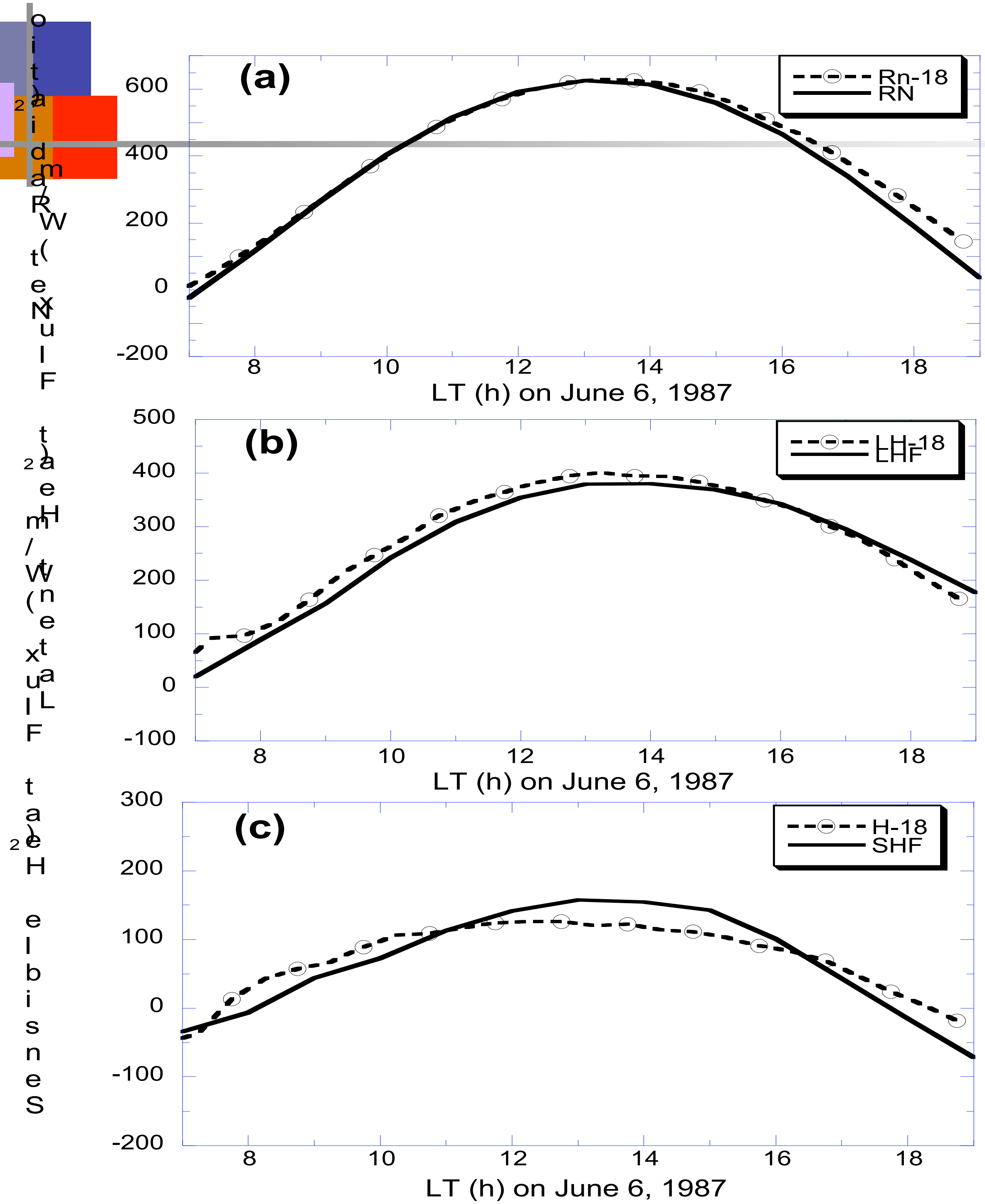
Land – Atmosphere Feedback are critical at different scales

- **Surface Energy Balance & Evapotranspiration**
- **Rn = Etr + Shf + storage; Etr = Eg+Tr**

- **Gradients in Surface Fluxes**
- **Non-classical Circulation**
- **Convection and Cumulus Formation**
- **Precipitation and Land Use Change**
- **Regional Climate Change**



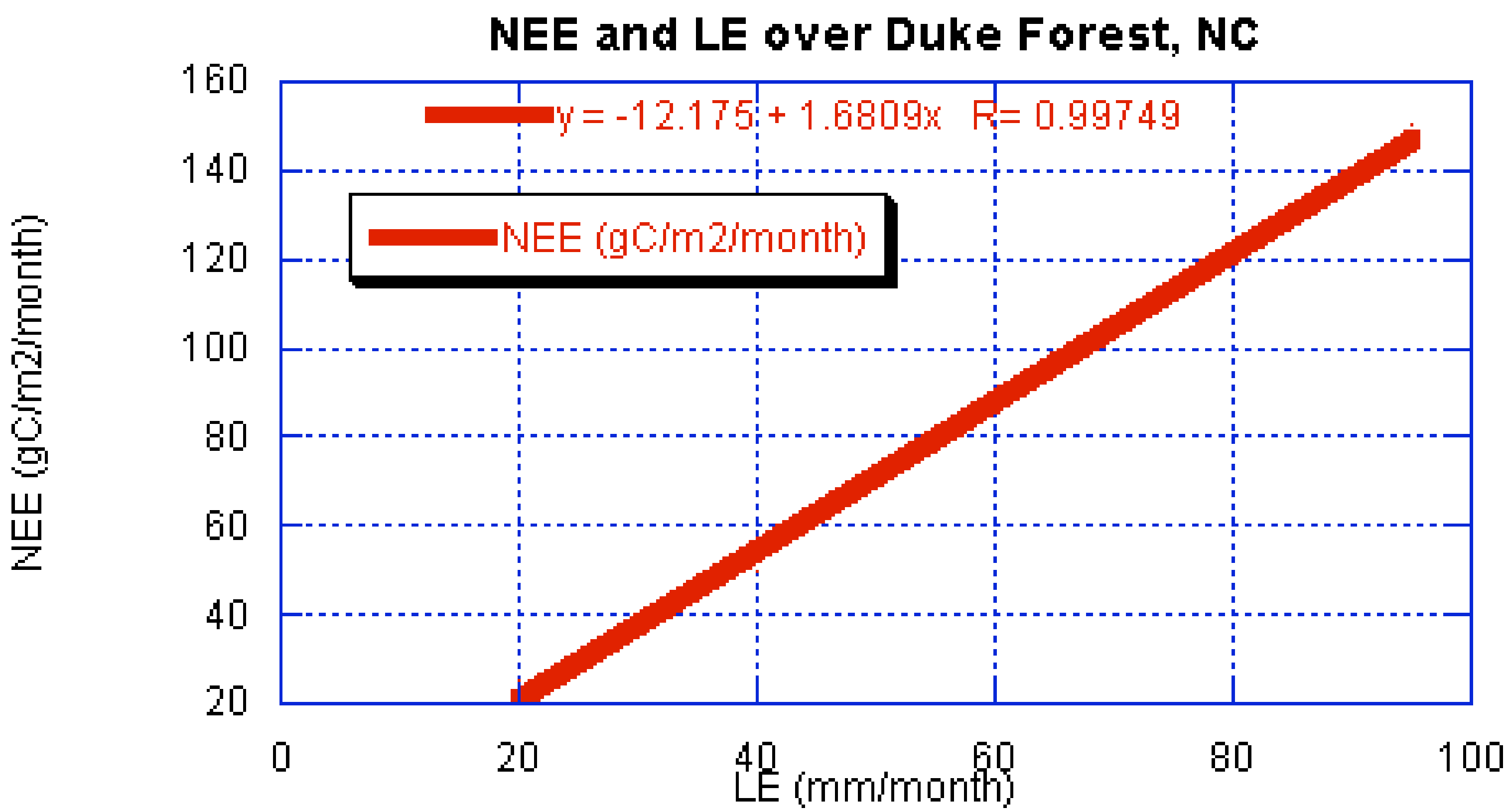

Macroclimatic conditions above the canopy
(Radiation fluxes, Temperature, air humidity etc.)
Structural characteristics of the canopy
(LAI, SAI, leaf and stem angles, spatial distribution of canopy elements)
Physical characteristics of the canopy elements
(Absorbance reflectance, transmittance, heat capacity etc.)
Physical laws
Spherical geometry
Microclimatic conditions within canopy subunits
Single leaf photosynthesis model
Species specific physiological characteristics
(photosynthetic capacity etc.)
Summing up over all canopy subunits
Canopy photosynthesis



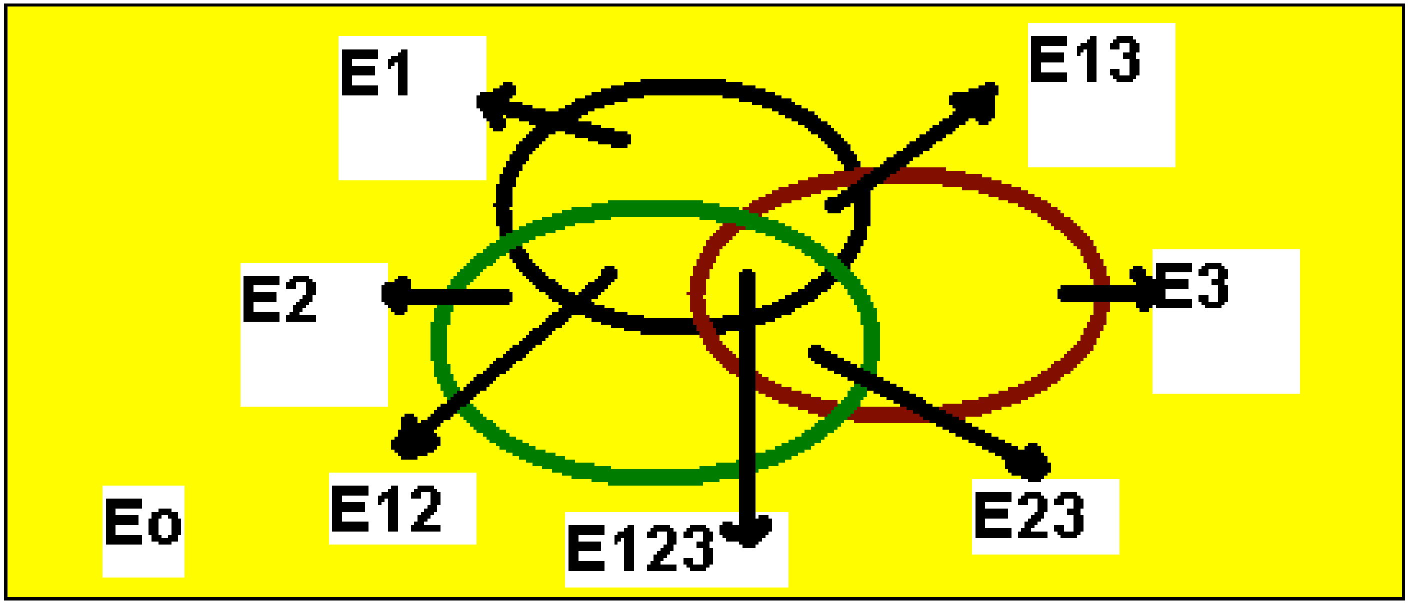
- Coupled BHA Model tested over several land surfaces in midlatitudes as well tropical conditions

e.g. FIFE, Mixed C4 grassland,

Coupled Hydrological and Carbon Exchanges

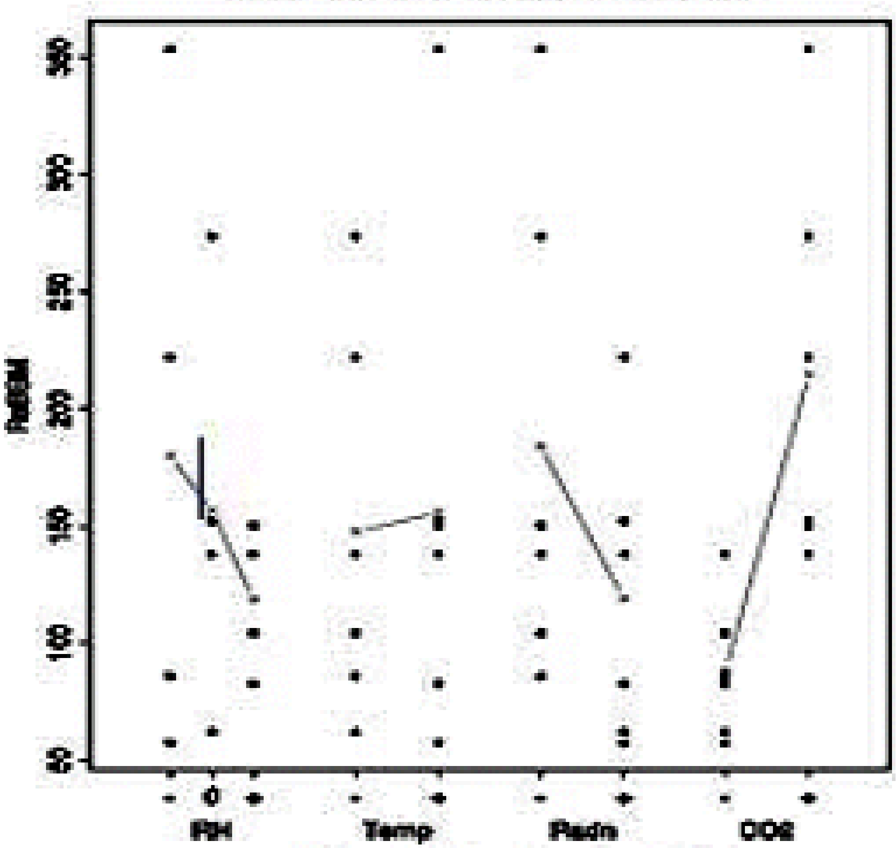


Considering interactions and feedback pathways

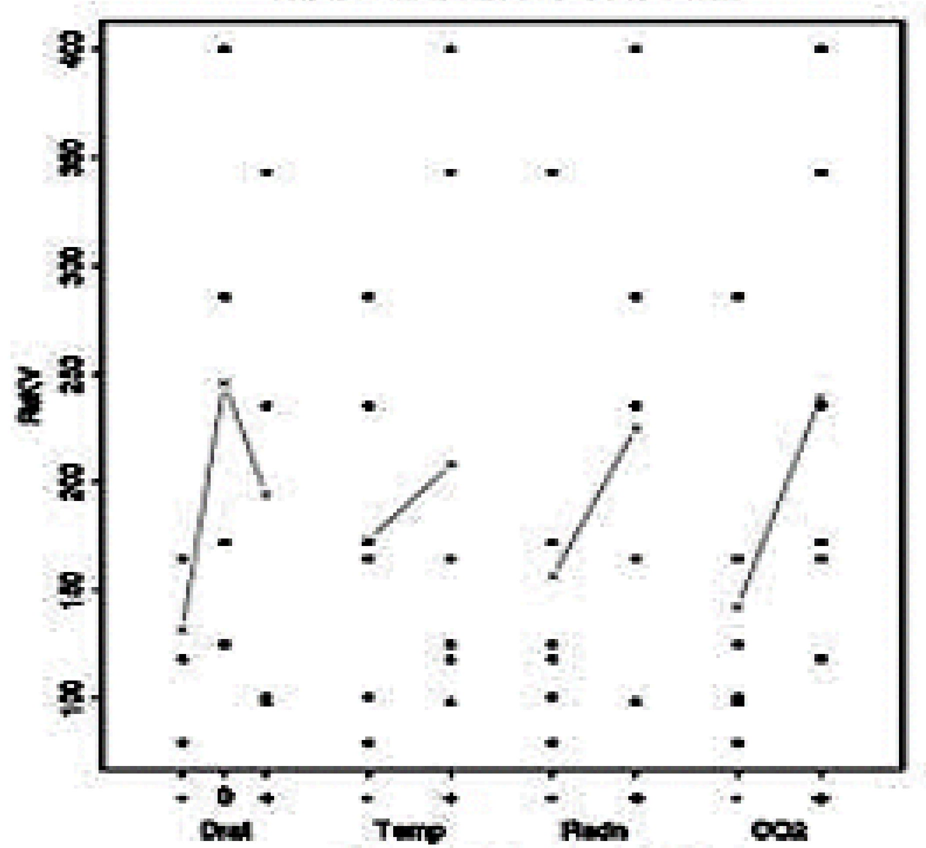


Resistance is affected by CO2 change, Net Radiation, Air Temperature, and Humidity.
All these factors affect Carbon Assimilation

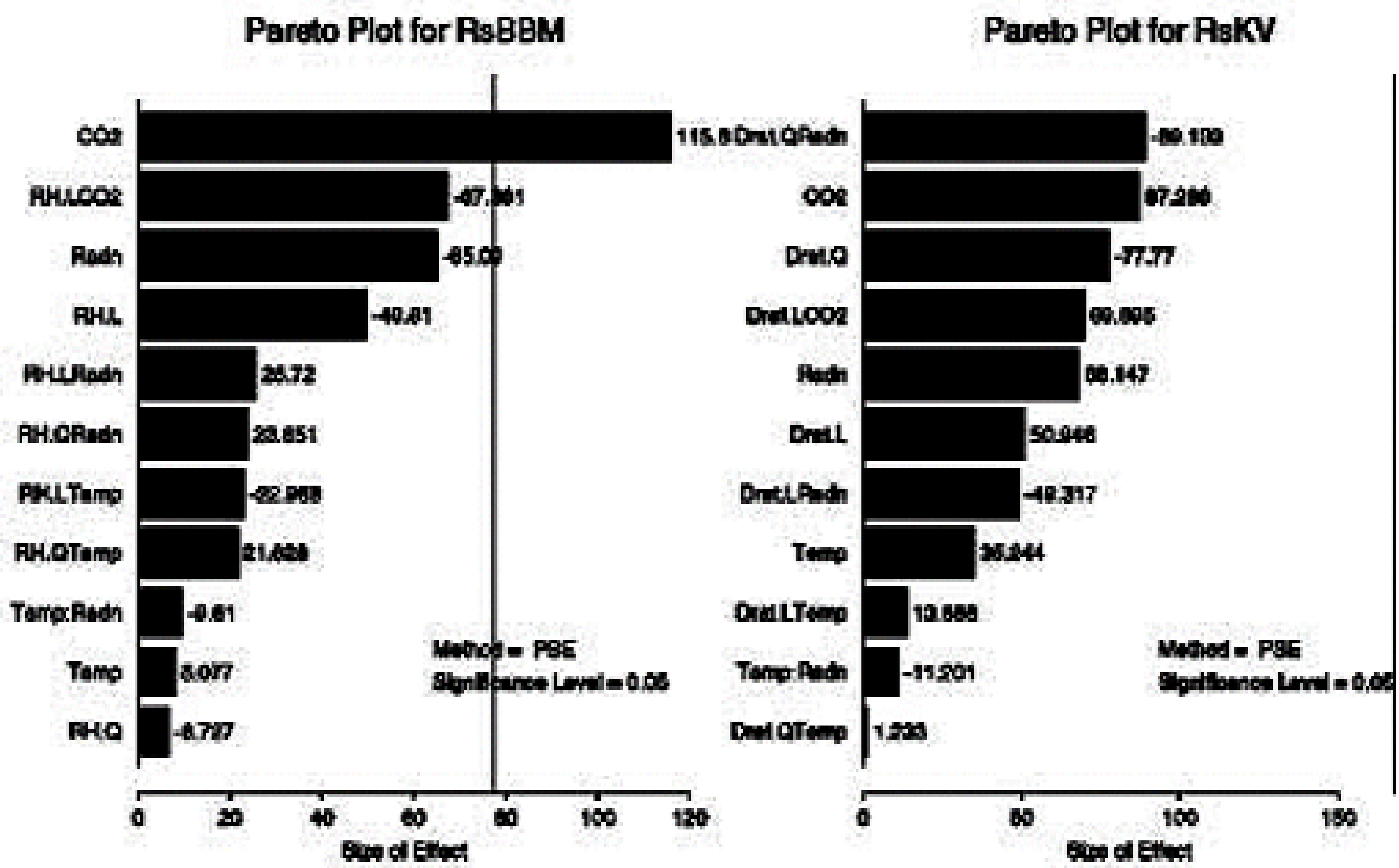
Main Effects Plot for RsBBM



Main Effects Plot for RsKV



Carbon Assimilation is greatly affected by the environmental feedback



How do LSP responses vary in tropics and midlatitudes?

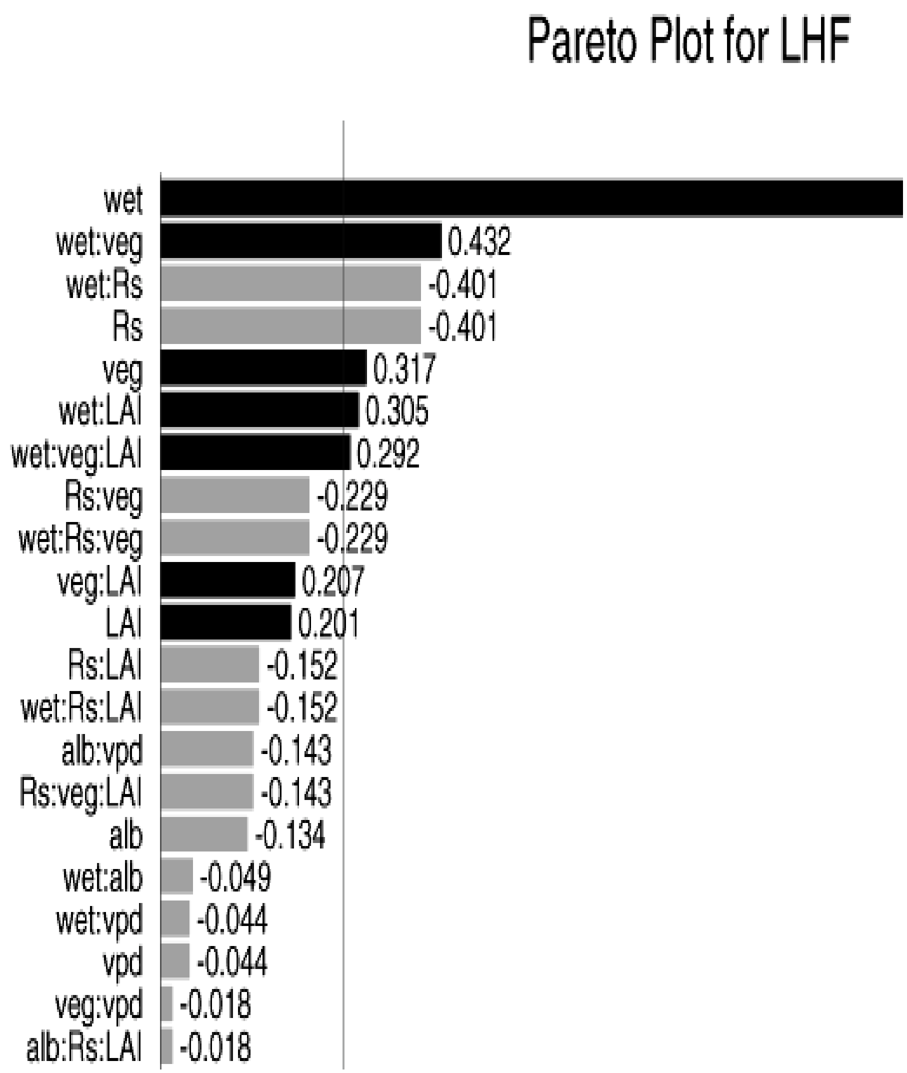
SSiB Input Conditions Varied in the 48 Simulations each (over tropics and midlatitudes)

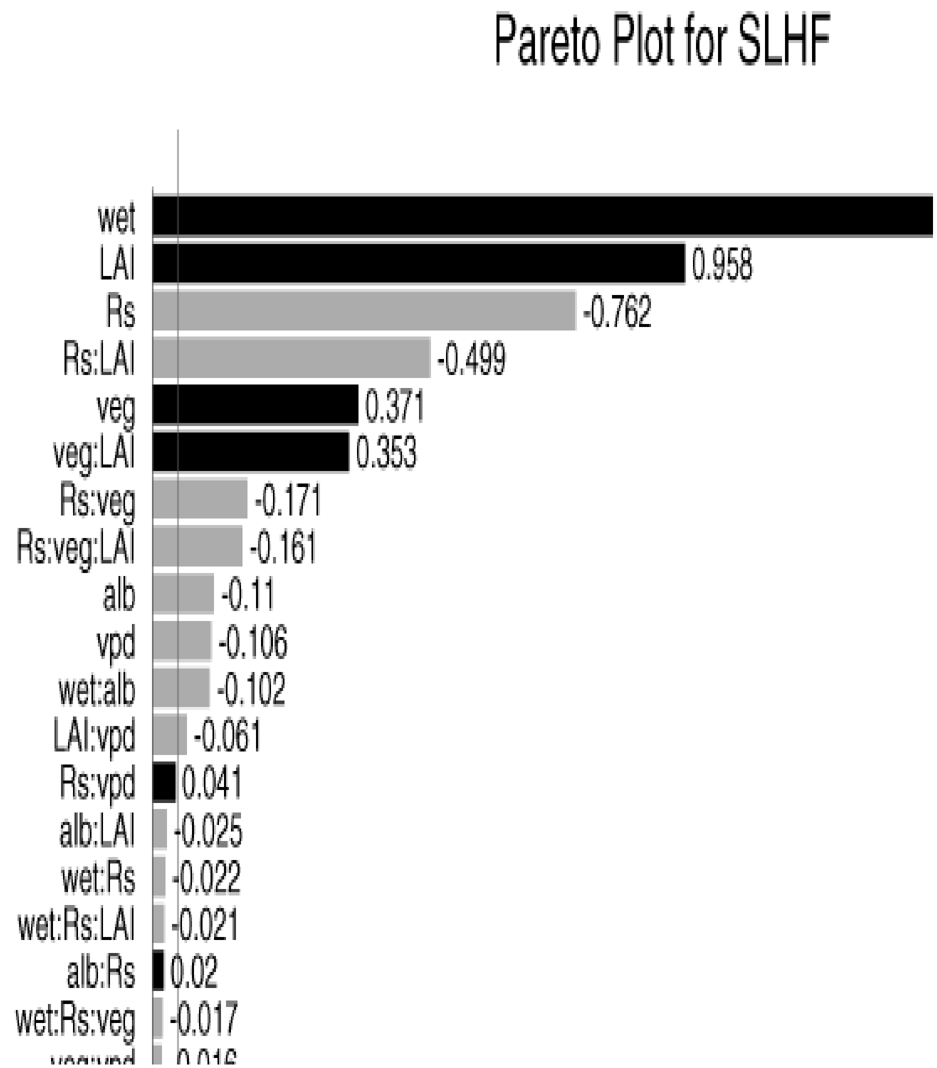
Variable	Setting		
	High (+)	Median (0)	Low (-)
wet ($m^3 m^{-3}$)	0.60	0.465	0.33
alb	0.25	0.20	0.15
Rs_{min} ($s\ m^{-1}$)	300	180	60
veg	0.9	0.5	0.1
LAI	3.0	1.75	0.5
vpd ($kg\ kg^{-1}$)	0.035	0.0275	0.020

Design matrix for setting the input variable values in SSiB

Run	Wet	Alb	Rs_{min}	veg	LAI	Vpd
1	-	-	-	-	-	-
2	-	-	-	-	+	+
3	-	-	-	+	-	+
4	-	-	-	+	+	-
5	-	-	+	-	-	+
6	-	-	+	-	+	-
7	-	-	+	+	-	-
8	-	-	+	+	+	+
9	-	+	-	-	-	+
10	-	+	-	-	+	-
11	-	+	-	+	-	-
12	-	+	-	+	+	+
13	-	+	+	-	-	-
14	-	+	+	-	+	+
15	-	+	+	+	-	+
16	-	+	+	+	+	-
17	+	-	-	-	-	+
18	+	-	-	-	+	-
19	+	-	-	+	-	-
20	+	-	-	+	+	+
21	+	-	+	-	-	-
22	+	-	+	-	+	+
23	+	-	+	+	-	+
24	+	-	+	+	+	-
25	+	+	-	-	-	-
26	+	+	-	-	+	+
27	+	+	-	+	-	+
28	+	+	-	+	+	-
29	+	+	+	-	-	+
30	+	+	+	-	+	-
31	+	+	+	+	-	-
32	+	+	+	+	+	+
33	-	0	0	0	0	0
34	+	0	0	0	0	0
35	0	-	0	0	0	0
36	0	+	0	0	0	0
37	0	0	-	0	0	0
38	0	0	+	0	0	0
39	0	0	0	-	0	0
40	0	0	0	+	0	0
41	0	0	0	0	-	0
42	0	0	0	0	+	0
43	0	0	0	0	0	-

Why land surface changes in tropics matter?





Tropics and Midlatitudinal LSPs

- LSPs affect both the ‘domains’
- Direct Effects are SIMILAR
- Interactions / Feedback Pathways show DIFFERENCES
- Semiarid Tropics vegetation interactions while Midlatitudes dominated by soil moisture related interactions
- Midlatitudinal case shows both vegetation and soil interactions
- Tropical case does not show vegetation and soil interactions (i.e. surface acts as independent mosaic of vegetation and soil acting interacting with ‘atmosphere’)
- More interactions –> more resilience -> lesser vulnerability ?
- Possible to review carbon – hydrological feedback process as an econometric / resource allocation approach in future analyses
- (Additional studies with detailed regional atmospheric modeling system in future)

Hydrological – Carbon Feedbacks

CO_2 issues need implicit hydrological considerations

e.g. Ball Berry carbon assimilation / transpiration model

$Gs = (m \cdot An / Cs \cdot RHs) + b$

- m, b - specie specific 'constants'
- An - Net Assimilation
- Cs - CO_2 at leaf surface
- RHs - humidity at leaf surface

→ Carbon Assimilation is linked with transpiration (which is linked with surface energy balance, and so on…)

→ Possible to scale carbon effects via hydrological considerations

Further analysis of CO_2 – hydrological interations

- Use a couple BHA (photosynthesis based) model
- Vary CO_2 (present day and doubling) and soil moisture (drought and no drought) conditions
- Simulate responses (carbon assimilation, air temperature, transpiration, and stomatal conductance) for all 9 global SiB2 vegetation types
- Experimental Design to replicate chamber / FACE – like setups I.e., pure SM – CO_2 analysis (coupled); (radiative feedback, regional feedbacks, switched off …)

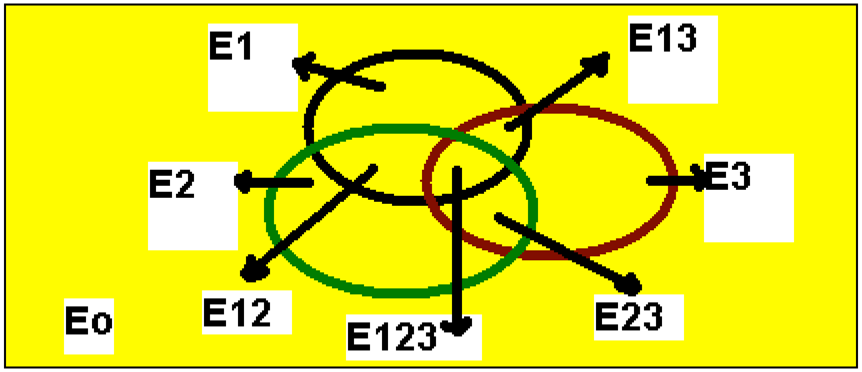
Interaction Explicit Analysis of effect of simultaneous soil moisture and CO_2 changes on terrestrial feedback

Eo = Fo = f [CO2 - , Moist -]

F1 = f [CO2 + , Moist -]

F2 = f [CO2 - , Moist +]

F12 = f [CO2 + , Moist +]

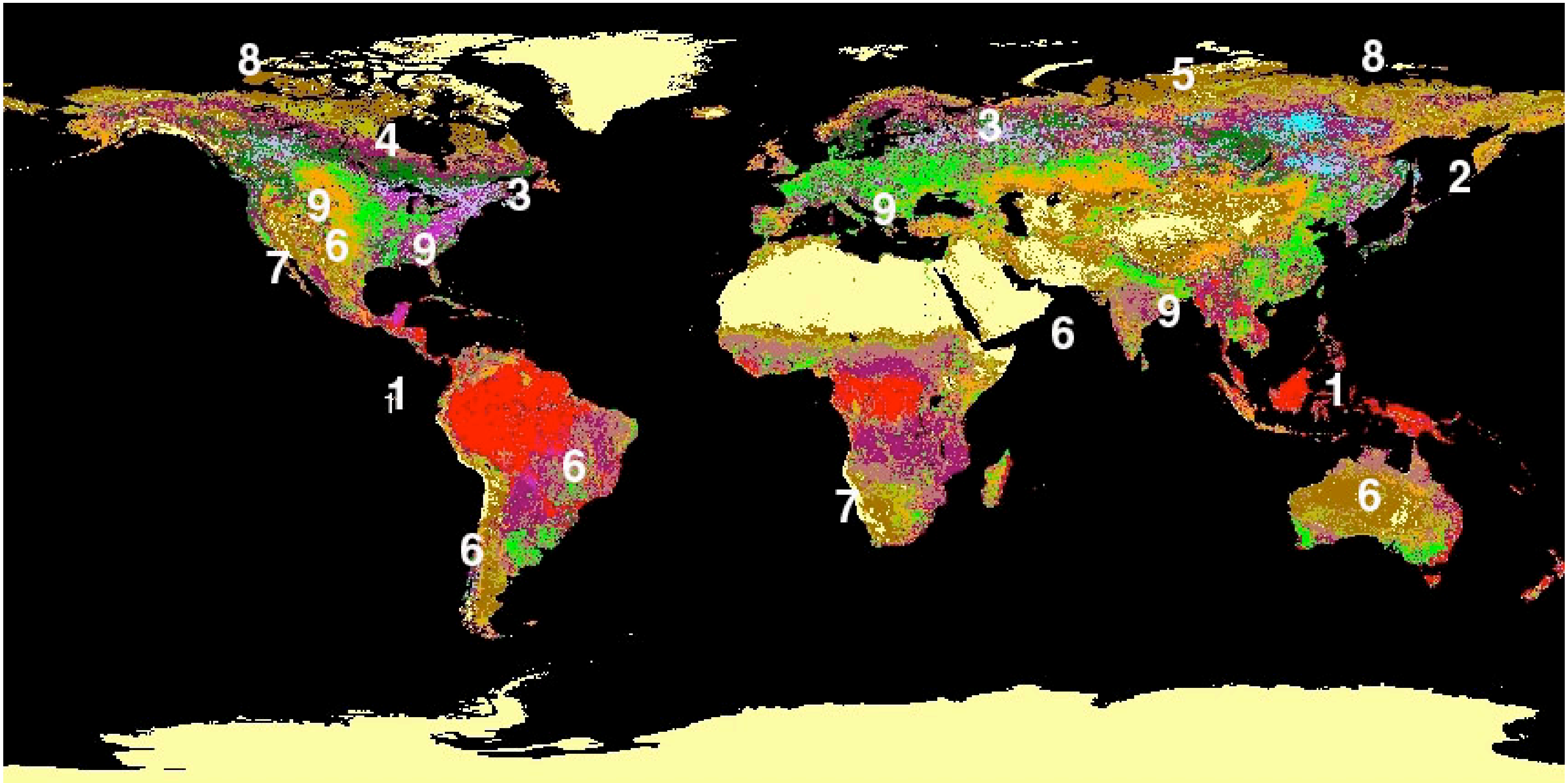


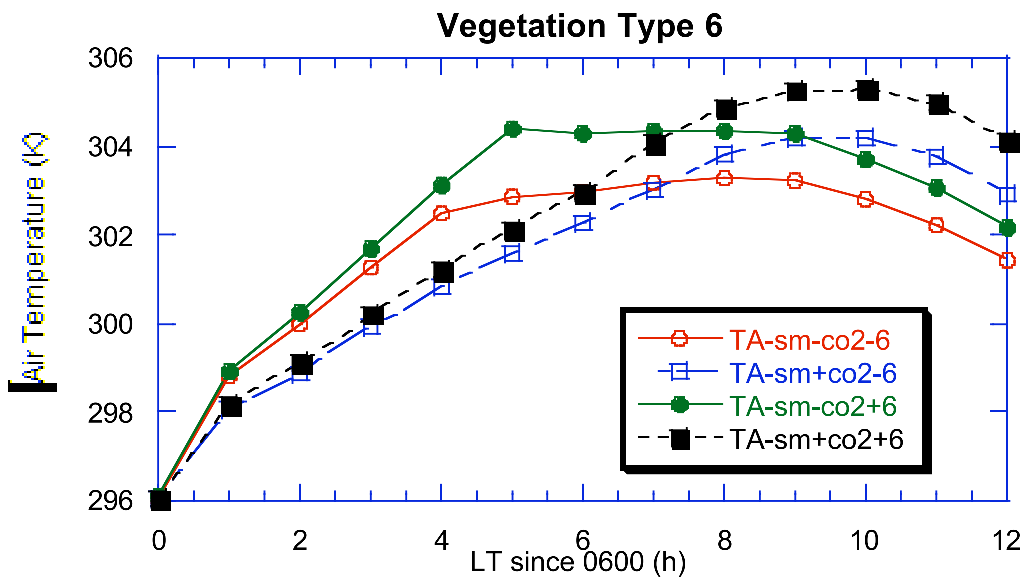
E(CO2) = F1 - Eo

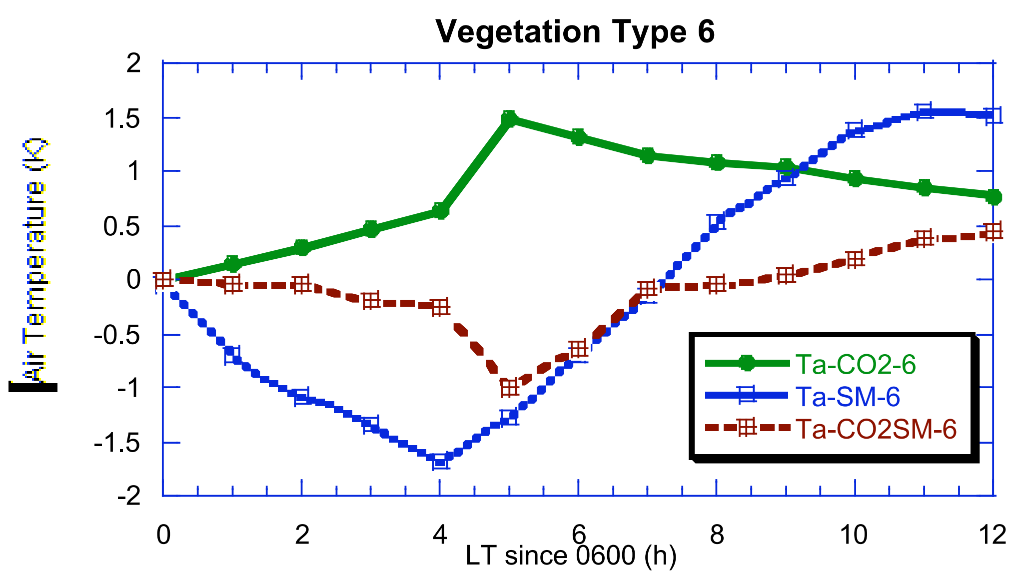
E(SM) = F2 - Eo

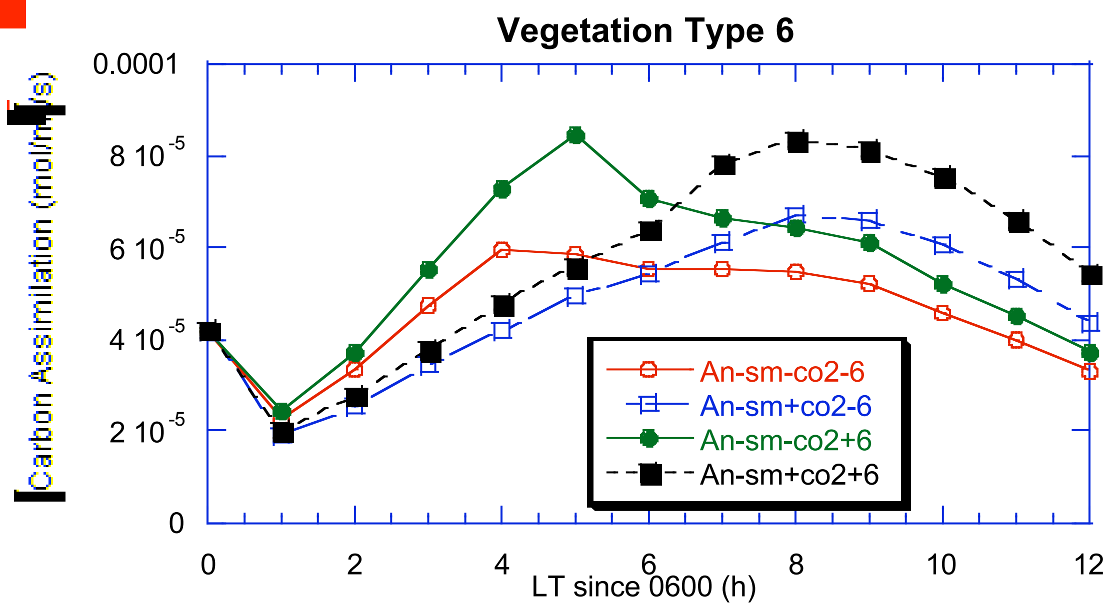
E(CO2:SM) = F12 - (F1+F2) - Fo

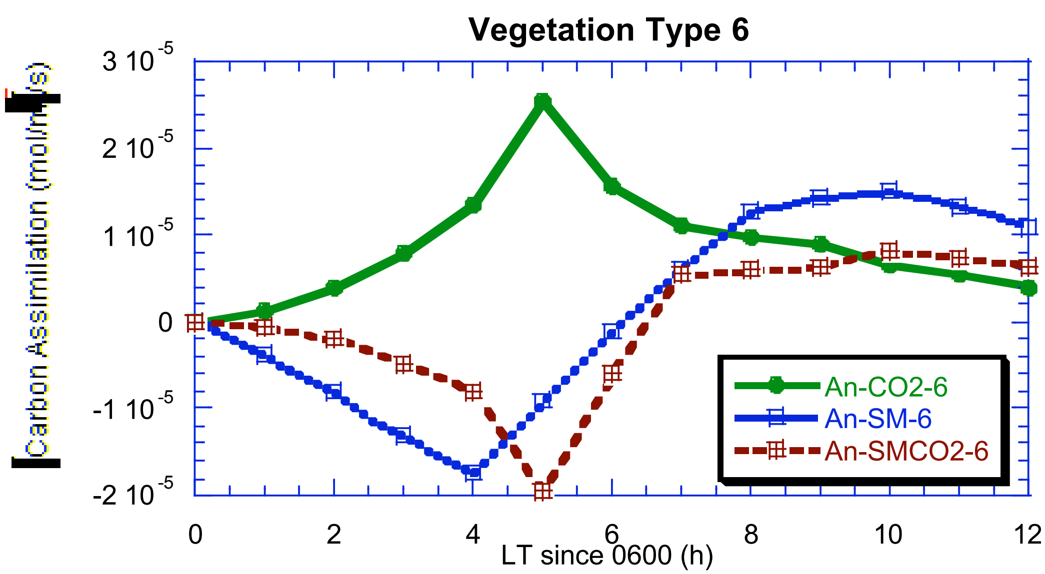
Global Vegetation Types. 1,2,3: ”Broad Trees” (~ 15%), 4,5: “Needle Trees” (~ 15%), 6: C4 Grass (~30%), 7,8,9: C3 shrubs/Crops (~30%); (Permafrost not considered)

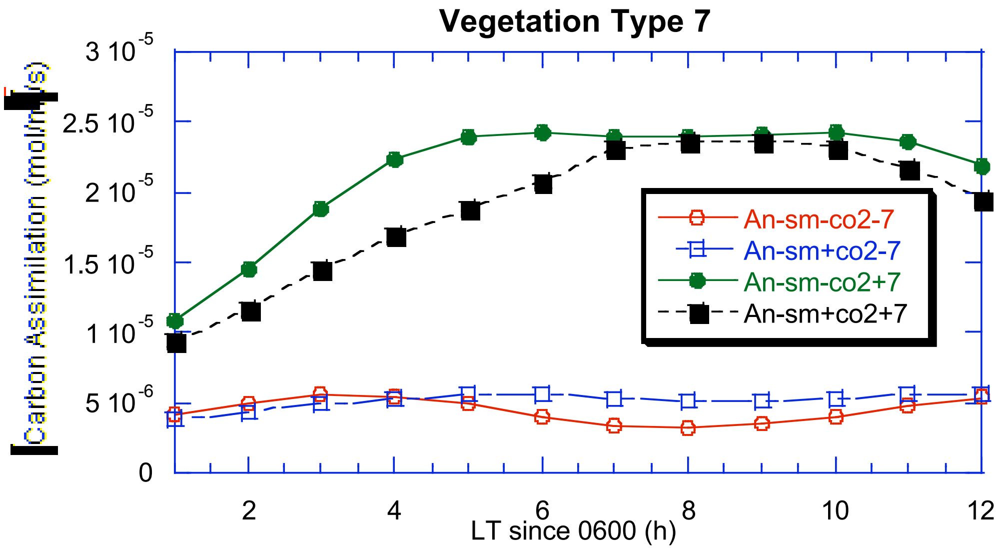


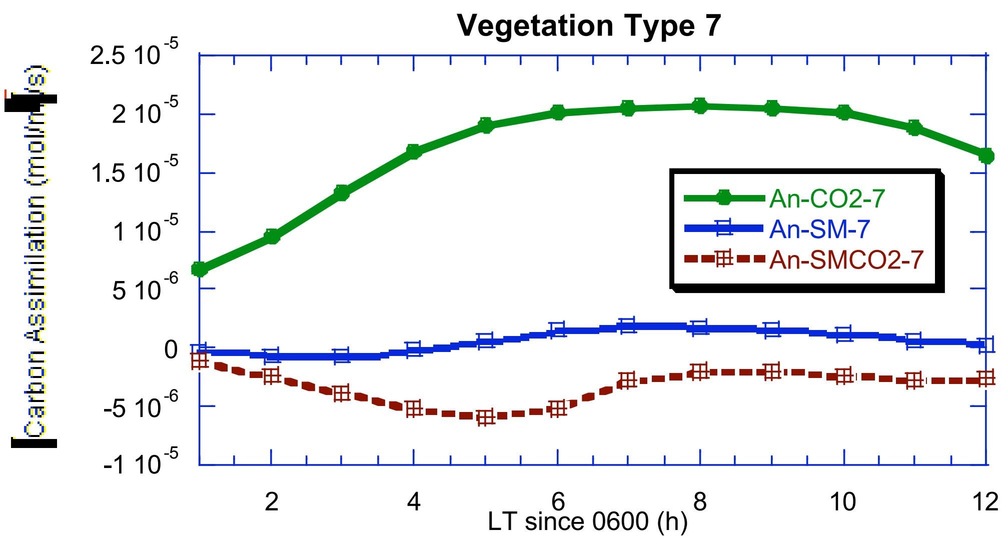

Vegetation Type 6
306
304
302
300
298
296
Air Temperature (K)
0
2
4
6
8
10
12
LT since 0600 (h)
TA-sm-co2-6
TA-sm+co2-6
TA-sm-co2+6
TA-sm+co2+6


Vegetation Type 6
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Air Temperature (K)
0
2
4
6
8
10
12
LT since 0600 (h)
Ta-CO2-6
Ta-SM-6
Ta-CO2SM-6


Vegetation Type 6
0.0001
8 10-5
6 10-5
4 10-5
2 10-5
0
Carbon Assimilation (mol/m2/s)
0
2
4
6
8
10
12
LT since 0600 (h)
An-sm-co2-6
An-sm+co2-6
An-sm-co2+6
An-sm+co2+6


Vegetation Type 6
3 10-5
2 10-5
1 10-5
0
-1 10-5
-2 10-5
Carbon Assimilation (mol/m2/s)
0
2
4
6
8
10
12
LT since 0600 (h)
An-CO2-6
An-SM-6
An-SMCO2-6


Vegetation Type 7
Carbon Assimilation (mol/m2/s)
3 10-5
2.5 10-5
2 10-5
1.5 10-5
1 10-5
5 10-6
0
2
4
6
8
10
12
LT since 0600 (h)
An-sm-co2-7
An-sm+co2-7
An-sm-co2+7
An-sm+co2+7


Vegetation Type 7
Carbon Assimilation (mol/m2/s)
2.5 10-5
2 10-5
1.5 10-5
1 10-5
5 10-6
0
-5 10-6
-1 10-5
2
4
6
8
10
12
LT since 0600 (h)
An-CO2-7
An-SM-7
An-SMCO2-7

Analysis for the “Broadleaf” trees (SiB2 vegetation types 1,2, and 3)

- Each vegetation type has characteristic response to the biotic and abiotic changes
- CO_2 Enrichment will lead to
  - Enhanced net primary productivity
  - Moderately decrease stomatal resistance
  - Marginally increase evapotranspiration (but increase WUE)
  - No significant effect on air temperature
- CO_2 - Soil Moisture interactions are active and often equal to the lesser dominant effect.
- Limiting soil moisture controls biospheric response irrespective of CO_2 levels; high soil moisture availability synergistically assist CO_2 effects (which are then dominant)

"Needleleaf" trees (SiB2 vegetation types 4 and 5)

- Each vegetation type has characteristic response to the biotic and abiotic changes
- Many of the features are similar as discussed for the "Broadleaf" trees, but with
  - significantly lowered both ETR, and NPP (WUE not changed)
  - Significantly higher soil moisture and CO_2 interaction effect
  - Respiration losses dominated by soil moisture availability

Analysis for the “C4” vegetation (SiB2 vegetation type 6)

- **Results similar to Nie et al. (1992) closed - chamber experiments**
- **Highest NPP values seen for doubling of CO_2 under limiting soil moisture conditions**
- **CO_2 increase reduced ETR significantly (opposite to broadleaf trees)**
- **Active and dominant CO_2 - Soil Moisture interactions**
- **Role of C4 grasslands as a source / sink carbon pathway will depend on the soil moisture availability (higher the moisture, more the respirative losses)**
- **Doubling of CO_2 increased air temperature by 1.5K but if accompanied by increasing soil moisture, induced relatively *cooling*, instead!**

Analysis for the C3 grass and shrubs (SiB2 vegetation types 7,8, and 9)

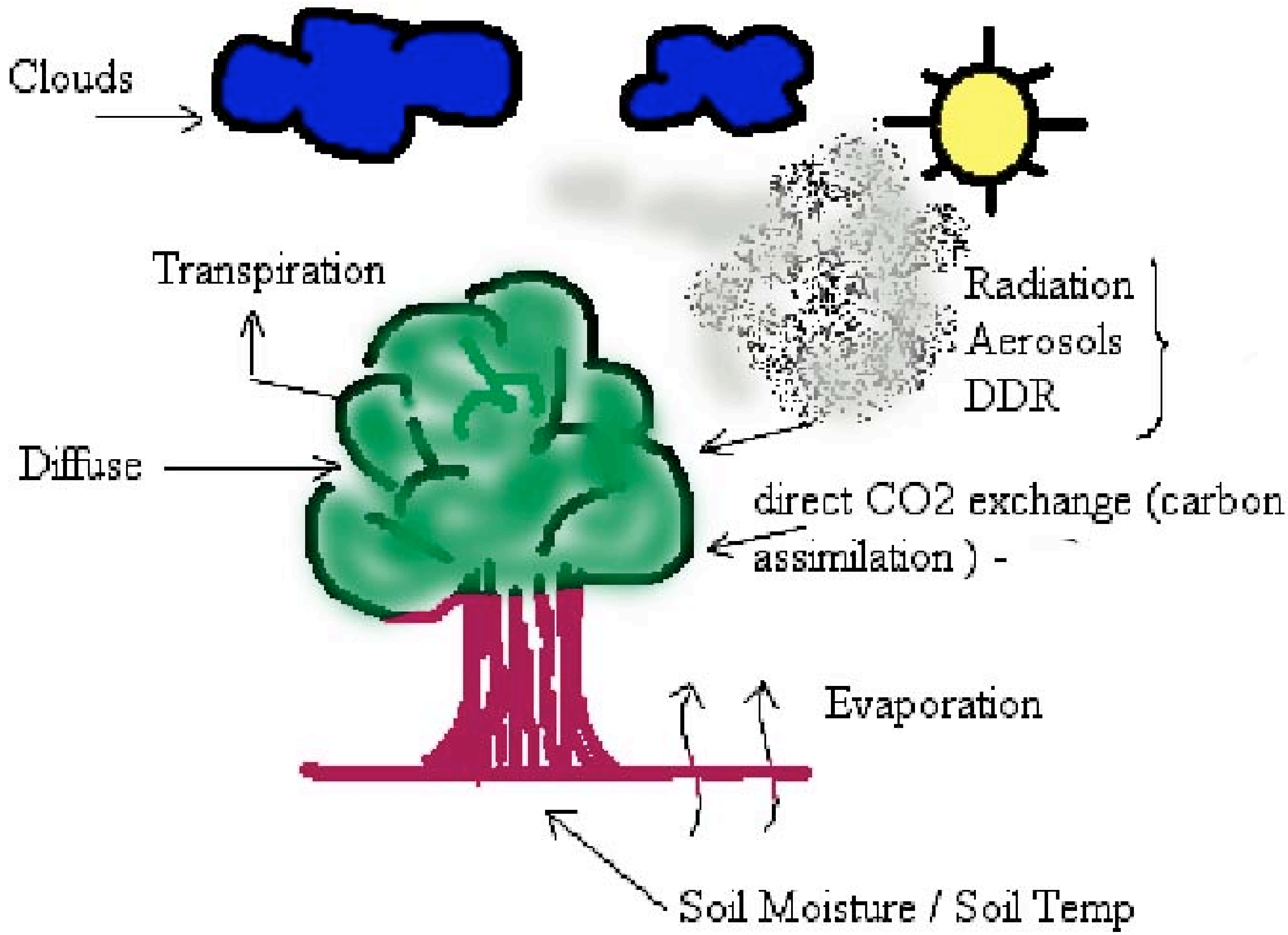
- Each vegetation type has characteristic response to the biotic and abiotic changes
- Many of the effects are opposite to those seen for C4 grass
- C3 - C4 shrub / grassland ecotone dominance will depend on the soil moisture availablity
- NPP is highest for resource “unlimiting” conditions (high soil moisture and doubling of CO_2 conditions)
- Interactions tend to balance the response and hence the outcome will not be as dramatic as seen in many one -at - a - time studies (Martin et al. 1989)

Relevance of the results to BAI studies

- Process - based analysis of the physical parameterizations for every vegetation - type
- Extracted direct as well as interactive feedbacks
- Interaction effects can be equated to the indirect effects of CO_2 doubling (though not causally, often as empirical corrections)
- Previous studies suggested, CO_2 doubling will affect C3 vegetation and may not affect C4. This may be true only for the direct effects but considering interactions, both C3 and C4 vegetation appears to be significantly affected by CO_2 changes
- CO_2 doubling effects should not be discussed without considering soil moisture status

- CO2 doubling is intrinsically linked with soil moisture availability
  - Used coupled GEM based outcome over all the nine SiB2 vegetation types to prove the hypothesis
  - landscape can be a source / sink depending on the soil moisture status
  - Need to consider interactions explicitly while analyzing BAI

LULC – Radiation – Aerosol – Hydrology- Carbon Assimilation Coupling



We wont know where we are going until we reach there..
We need to be prepared for diverse scenarios…
Understanding / accounting for the feedback effects and the resulting vulnerability (using models as assessment tools) will help address an integrated assessment on global (climate) change
Any LULC change -even with the best of management and mitigation interests in mind- may prove to be a failure and even harmful unless we explicitly consider the feedback processes affecting the CO2 (and hydrological interactions) for an effective resilient policy

- *Where do we go from here?*

- Correct and Robust science that will generate defensible and testable results should be the key, currency (C, J, W/m2…) can be interchanged
- Incorporate LULC change as a critical driver for global climate change
- Need to develop projects and approaches for validating the testable hypotheses
- Scaling (time and space based) still remains the biggest disconnect
- Need for intelligent adaptive models (combining processes with optimization concepts for process simulations e.g. drought adaptation, invasion….)

THANK YOU !!